Predicting the Power Loss of Reciprocating Compressor Manifolds

Project Team:

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Project Motivation

How much power does my compressor need?
Compressor Performance Calculation

Why Estimated Total Load?
- Compression (ideal) power ✔
- Mechanical Efficiency ✔
- Manifold (bottle) power loss ??
- Orifice power loss ??
- Other system loss ??

How do you calculate the unknown power losses?
Compressor Performance Calculation

Unknown Power Losses are estimated by the pressure drop

<table>
<thead>
<tr>
<th>Stage/Service Data</th>
<th>Stage-1</th>
<th>Stage-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow Rate: MMBtu/h</td>
<td>5.82</td>
<td>5.82</td>
</tr>
<tr>
<td>Head: HP</td>
<td>449.3</td>
<td>377.2</td>
</tr>
<tr>
<td>Specific Gravity:</td>
<td>0.5660</td>
<td>0.5660</td>
</tr>
</tbody>
</table>

Suction Press.: psiA
Ps@Flange: psiA
Pd@Flange: psiA
Discharge Press.: psiA

Order Status: IPS 7500743

How much, assume 1%, 2%? Is it accurate?
Pressure Drop Calculation... easy, right?

\[ h_{loss} = K \frac{V^2}{2g} \]

OK, but...does this work for my recip compressor?
Challenges to Industry

• Manifolds (pulsation bottles) have complicated geometry. K-factors are not published.

• Recip compressors create high flow fluctuations.

• How to relate pressure drop to power loss?
How important is power loss?

Inaccurate power calculation effects performance and reliability (3% to 12% error in results)

Consequences:
- Driver size inadequate
- Unable to meet contract flow
- Reliability (rod load, reversal, and discharge temperature)
- Inefficient operation
1. Develop a **methodology** to predict the mean and pulsating power losses across Reciprocating Compressor Manifolds (bottles).

2. **Validate** the methodology via experimental means, either from:
   - Measurements of actual recip. compressor in the field, or
   - Scale-down test rig involving a custom-design bottle and a Pulse-generator.

3. **Ultimate Goal** is to:
   - Recommend a standard methodology to quantify the pulsating flow power loss.
   - Come up with adjustment factor(s) to be applied to the mean pressure drop coefficient (K) in the presence of pulsating flow.
Overall Project Objectives

1. **Completed 2013** Develop a methodology to predict the mean and pulsating power losses across Reciprocating Compressor Manifolds (bottles).

2. **Validate** the methodology via experimental means, either from:
   - Measurements of actual recip. compressor in the field, or
   - **Scale-down test rig involving a custom-design bottle and a Pulse-generator.**

3. **Ultimate Goal** is to:
   - Recommend a standard methodology to quantify the pulsating power loss.
   - Come up with adjustment factor(s) to be applied to the mean pressure drop coefficient (K) in the presence of pulsating flow.

**Focus of this presentation**
Outline

1. Test Program
2. Measurements and Results
3. Key Findings
4. Next Steps
Test Setup at TCPL’s GDTF in Didsbury, Alberta
Pulse Generator

Pulsations will be created by a hydraulically driven rotating paddle

- Not a recip compressor
- Operate at 300 to 1200 rpm.
- Double acting
- Pulse amplitude 1% to 2% line pressure
Test Setup Details

**Configuration A:** Bottle Upstream, Orifice Downstream

**Configuration B:** Orifice Upstream, Bottle Downstream
Custom Bottle Design (donated by Peerless Mfg.)

It would be preferred that the nozzle in item 11 be constructed with 4" S40 pipe. Although pressure vessel code must still be met.
End Treatments

2-11-1/2 NPSM Straight Pipe Tapped Thread

2" Sch XS

2" x 3" Diffuser

Taper

Normal (Square)
Photos of Configuration A Setup
Pair of Dynamic P Transducers (1.5 m apart)

Static P & T Transducers (Upstream)

Kulite P Transducers
Pair of Dynamic P Transducers (1.5 m apart)

Kulite P Transducers
Pair of Dynamic P Transducers
(1.5 m apart)

Rosemount Differential P Transducer
Pair of Dynamic P Transducers (1.5 m apart)

Kulite P Transducers

Static P & T Transducers (Downstream)
Photos of Configuration B Setup
\[ B = 0.5 \]

\[ B = 0.7 \]

Diffuser

Taper

GMC Nashville Oct 5-8, 2014
Example of Pulsating Pressure Measurements (Across the Bottle)
Example of 1st Harmonic Mapping ($\mathbf{P}_k$ and $\mathbf{u}_k$) (Configuration A)

- **Test 27** (40.5 Hz, 6 Nozzles, 0.5 Beta)
- Acoustic Power = 0.2W
- Acoustic Power = 334W
- Acoustic Power = 380W
- Acoustic Power = 229W

Distance From Upstream 8"/4" Reducer (m)

- Pressure Amplitude (kPa)
- Velocity Amplitude (m/s)
Example of 1\textsuperscript{st} Harmonic $\overline{P}_k$ and $\overline{u}_k$ Mapping

(Configuration B)

Test 209

(15.875 Hz, 6 Nozzles, 0.5 Beta)

Acoustic Power = 44W
Acoustic Power = 248W
Acoustic Power = 391W
Acoustic Power = 100W
Test Results
(Configuration A)
### Configuration A Test Scope

<table>
<thead>
<tr>
<th>Test</th>
<th>Number of Sonic Nozzles</th>
<th>End Treatments</th>
<th>Orifice $\beta$</th>
<th>Hole(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3 and 6</td>
<td>Square/Square</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>1a</td>
<td>3 and 6</td>
<td>Square/Square</td>
<td>0.5</td>
<td>Single</td>
</tr>
<tr>
<td>1b</td>
<td>3 and 6</td>
<td>Square/Square</td>
<td>0.5</td>
<td>Multiple</td>
</tr>
<tr>
<td>1c</td>
<td>3 and 6</td>
<td>Square/Square</td>
<td>0.7</td>
<td>Single</td>
</tr>
<tr>
<td>1d</td>
<td>3 and 6</td>
<td>Square/Square</td>
<td>0.7</td>
<td>Multiple</td>
</tr>
<tr>
<td>2</td>
<td>3 and 6</td>
<td>Square/Diffuser</td>
<td>0.5</td>
<td>Single</td>
</tr>
<tr>
<td>3</td>
<td>3 and 6</td>
<td>Taper/Diffuser</td>
<td>0.5</td>
<td>Single</td>
</tr>
<tr>
<td>4</td>
<td>3 and 6</td>
<td>Taper/Square</td>
<td>0.5</td>
<td>Single</td>
</tr>
<tr>
<td>4a</td>
<td>High flow</td>
<td>Taper/Square</td>
<td>0.7</td>
<td>Single</td>
</tr>
</tbody>
</table>

For each of the sub-configuration and flow rate, a total of 10 tests were conducted at the following frequencies: 0, 11, 13, 15, 17, 22, 27, 31, 35, and 41 Hz. (Total for Configuration A = 180 Tests).
Normalized Pulsating Power Loss (Bottle)

Configuration A: Bottle

- Square/Square Orifice, Beta = 0.5, Single Hole
- Square/Square Orifice, Beta = 0.5, Multiple Holes
- Square/Square Orifice, Beta = 0.7, Single Hole
- Square/Square Orifice, Beta = 0.7, Multiple Holes
- Square/Square No Orifice
- Square/Diffuser Orifice, Beta = 0.5, Single Hole
- Taper/Square Orifice, Beta = 0.5, Single Hole
- Taper/Diffuser Orifice, Beta = 0.5, Single Hole

Normalized Pulsation Power Loss ($W_p/pcA_{rms}^2$)

Normalized Velocity Oscillation at Bottle Flange or Orifice Plate ($u_{rms}/U$)

GMC Nashville Oct 5-8, 2014
Normalized Velocity Oscillation $u_{\text{rms}}/U$

- **TGP Station 54**: 8350 HP compressor, 6 throw
  - $u_{\text{rms}}/U=0.7-1.3$
- **Gathering compressor**: 1775 HP, 4 throw
  - $u_{\text{rms}}/U=0.75$
- **Vapour Recovery Compressor**: 1200 HP, 6 throw
  - $u_{\text{rms}}/U=0.4$
- **Test Setup**: Hydraulic driven rotating paddle, 2 HP
  - $u_{\text{rms}}/U=0.3$ max

Current test setup representative of lower power/throw applications.

Pulse Generator modifications could generate $u_{\text{rms}}/U=0.6$
Normalized Pulsating Power Loss (Orifice)

Configuration A: Orifices

- Beta = 0.5
- Beta = 0.7

Normalized Pulsation Power Loss

Normalized Velocity Oscillation at Bottle Flange or Orifice Plate ($u_{rms}/U$)
Normalized Mean Flow Pressure Loss Coefficient (Bottle) – zoomed in

Configuration A: Bottle

Mean Flow Pressure Loss Coefficient, $K$

Normalized Velocity Oscillation at Bottle Flange or Orifice Plate ($u_{rms}/U$)
Theoretical $K$ Factor for the Bottle with Square End Treatments

### Bottle Theoretical $K$ Coefficient

<table>
<thead>
<tr>
<th>Element</th>
<th>Local $K$-Factor</th>
<th>$K$-Factor (Ref NPS4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NPS 4, ID (d2)</td>
<td>4.026</td>
<td>in</td>
</tr>
<tr>
<td>Choke Tube ID (d1)</td>
<td>1.939</td>
<td>in</td>
</tr>
<tr>
<td>Vessel ID (D)</td>
<td>14.29</td>
<td>in</td>
</tr>
<tr>
<td>Choke tube (L)</td>
<td>26</td>
<td>in</td>
</tr>
</tbody>
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<th>Element</th>
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</tr>
</thead>
<tbody>
<tr>
<td>Entrance to Bottle, $K_1$</td>
<td>0.85</td>
<td>0.85</td>
</tr>
<tr>
<td>Entrance to Choke Tube (square), $K_2$</td>
<td>0.49</td>
<td>9.11</td>
</tr>
<tr>
<td>Choke Tube (f=0.014), $K_3$</td>
<td>0.19</td>
<td>3.49</td>
</tr>
<tr>
<td>Choke Tube Exit (square), $K_4$</td>
<td>1.00</td>
<td>18.59</td>
</tr>
<tr>
<td>Entrance from Bottle to NPS4, $K_5$</td>
<td>0.42</td>
<td>0.42</td>
</tr>
<tr>
<td>Sum (Overall $K$)</td>
<td></td>
<td>32.45</td>
</tr>
</tbody>
</table>

Measured $K$ Factor

|                | 25              |

$K$ is 21% lower than expected. Why?
Thoughts about why the Measured $K$ Factor for the Bottle is Lower than Theoretical Value
Quasi-Steady Hypothesis of Mean Flow Pressure Drop in the Presence of Pulsating Flow

| Freq (Hz) | 27    |
| Omega (rad/s) | 169.646 |
| T (s)   | 0.037037 |
| U (m/s) | 16    |
| K      | 25    |
| Density (kg/m³) | 40    |
| Mean DP, no pulsation (kPa) | 128  |
Quasi-Steady Hypothesis of Mean Flow Pressure Drop in the Presence of Pulsating Flow

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</tr>
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<td>Mean DP, no pulsation (kPa)</td>
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<td>128</td>
</tr>
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</table>
Quasi-Steady Hypothesis of Mean Flow Pressure Drop in the Presence of Pulsating Flow

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
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<td>27</td>
</tr>
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<td>K</td>
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<td>40</td>
</tr>
<tr>
<td>Mean DP, no pulsation (kPa)</td>
<td>128</td>
</tr>
</tbody>
</table>

Mean Pressure Drop

Pressure Drop (kPa) vs. Time (s)
Quasi-Steady Hypothesis of Mean Flow Pressure Drop in the Presence of Pulsating Flow

| Freq (Hz) | 27 |
| Omega (rad/s) | 169.646 |
| T (s) | 0.037037 |
| U (m/s) | 16 |
| K | 25 |
| Density (kg/m3) | 40 |
| Mean DP, no pulsation (kPa) | 128 |

\[ y = x^2 + 1 \]
Current Measurements of Mean Flow Pressure Loss Coefficient (Representative of Suction Bottle)
Normalized Mean Flow Pressure Loss Coefficient (Orifice) – Referenced to NPS4

Configuration A: Orifices

$K_{\text{theoretical}}$ (for $\beta = 0.5$) = 29.7

$K_{\text{theoretical}}$ (for $\beta = 0.7$) = 4.3

Normalized Velocity Oscillation at Bottle Flange or Orifice Plate ($u_{\text{rms}}/U$)
Test Results
(Configuration B)
Configuration B Test Scope

For each of the sub-configuration and flow rate, a total of 10 tests were conducted at the following frequencies: 0, 11, 13, 15, 17, 22, 27, 31, 35, and 41 Hz. (Total for Configuration B = 160 Tests)
Normalized Pulsating Power Loss (Bottle)

Configuration B: Bottle

- Square/Square Orifice, Beta = 0.5, Single Hole
- Square/Square Orifice, Beta = 0.5, Multi-hole
- Square/Square Orifice, Beta = 0.7, Single Hole
- Square/Square Orifice, Beta = 0.7, Multi-hole
- Square/Diffuser Orifice, Beta = 0.5, Single Hole
- Taper/Square Orifice, Beta = 0.5, Single Hole
- Taper/Diffuser Orifice, Beta = 0.5, Single Hole

Normalized Pulsation Power Loss ($W_p/pcA_{rms}^2$)

Normalized Velocity Oscillation at Bottle Flange or Orifice Plate ($u_{rms}/U$)
Current Measurements of Mean Flow Pressure Loss Coefficient (Representative of Discharge Bottle)

- Quasi-Steady Pressure Drop Relationship
  - Square/Square
  - Square/Diffuser
  - Taper/Square
  - Taper/Diffuser

\[ y = x^2 + 1 \]
Summary of Site Testing

1. **Methodology**: Successful in validating the Flow Energy (acoustic power) methodology developed in Phase I.

2. **Bottle**: Differences measured between the bottle loss factor in steady flow and fluctuating flow as compared to published data. A 21% difference for steady flow, 5% for fluctuating flow in the test rig.

3. **Orifice**: Loss factor for single hole vs multi hole agreed well with published data. Some divergence at maximum test frequency of 41 Hz. Additional testing to investigate higher frequencies.

4. **Pulse Generator**: could create sufficient pressure fluctuations (2% of line) but flow fluctuations were lower than high power compressor cylinder ($u_{rms}/U < 0.3$).
## 2014 Project Plan

<table>
<thead>
<tr>
<th>Task</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Field Test</strong></td>
<td>Testing completed July 25</td>
</tr>
<tr>
<td>- Design test rig</td>
<td>Data review and analysis 95% completed.</td>
</tr>
<tr>
<td>- Fabricate and Install</td>
<td></td>
</tr>
<tr>
<td>- Execute Test Plan</td>
<td></td>
</tr>
<tr>
<td>- Data Analysis</td>
<td></td>
</tr>
<tr>
<td><strong>Report</strong></td>
<td>Complete by end of 2014</td>
</tr>
<tr>
<td><strong>Optional Scope: Testing on reciprocating compressor facility</strong></td>
<td>Need a site: TGP Stn 54, lots of information from Phase 1. Other site possible.</td>
</tr>
<tr>
<td></td>
<td>Design test:</td>
</tr>
<tr>
<td></td>
<td>- Fluctuation flow measurement</td>
</tr>
<tr>
<td></td>
<td>- Compressor performance (P-V curves) and power measurements (torque, motor power)</td>
</tr>
</tbody>
</table>
Suggestions for Future Work

- Addition testing proposed at the TCPL site. Redesign of pulse generator or test rig required to create high flow fluctuations. CFD analysis of components.

- 4 possible journal publications resulting from the work completed.
Thank You and Acknowledgements

- GMRC for Funding the Research Program
- PSC Oversight committee
- Peerless Mfg. (Dave Breindel) for fabricating and donating the Custom Bottle Design used in the present testing program.
- TCPL (Thomas Robinson) for the in-kind contribution of the use of the GDTF in Didsbury, Canada.
- The following individuals for assisting in conducting the tests and data analysis:
  - Matthew Kindree, Alex Mantey (NRTC)
  - Bill Eckert, Mark DuBois, Mehdi Arjmand (Beta)
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